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# Scaling Effects in Carbon/Epoxy Laminates Under Transverse Quasi-Static Loading

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# Introduction

Composites are increasingly being used in applications where strength to weight considerations are a design requirement. These applications rely on an understanding of the failure process of the composite so that structural failure is avoided. As a result, it is necessary to ensure that effective methods of predicting different modes of failure can be developed.

However, due to the complex anisotropic and non-homogeneous nature of composite laminates, theoretical models for failure are difficult to formulate and are prone to errors. The composite design process is further hindered by the lack of the broad material property database available for traditional engineering materials. Thus, a typical part of the composite structural design process is usually a destructive mechanical evaluation of prototype (or full-scale) elements.

Such mechanical analyses usually require a sizable investment of finances and time. Accordingly, many investigators (references 1-10) have shown an interest in applying the theory of similitude to composite structures. The theory of similitude involves a dimensional analysis which correlates a scale model's behavior to the behavior of the larger prototype. This form of analysis has served as an extremely useful aerodynamic design tool correlating the flight characteristics of a scale model to the full scale application. It is hoped that this success will soon be available for the mechanical response of composite structures.

The present study explores three areas associated with a quasi-static transverse loading event on composite plates. First, the scaleability of the mechanical behavior is examined. Second, the correlation of indentation depth to internal damage is examined. Finally, the mode and extent of failure for plates impacted at low velocity and quasi-statically is examined.

## Scale Effects

One of the shortcomings of composites in the design process is their complex failure behavior. As a result, the design process includes extensive destructive evaluation of prototypes (full-scale articles) which is usually expensive and time consuming. The composite design process is further plagued by the lack of a data base for the numerous fiber and matrix combinations. In order to be able to run large numbers of tests to evaluate the many variables and use simpler analysis, scaled down samples can be used with dimensional analysis (scaling rules).

However, scale modeling of fiber reinforced laminates is limited. Ideally the fiber diameter would also be scaled down, but this is not possible, so scaling must be done on a more macroscopic level. A laminate can have the thickness of each of its plies scaled by adjusting the number of grouped plies of similar orientation. This is referred to as ply-level scaling. For example, the thickness of a $[+45_2,0_2,-45_2,90_2]_S$ laminate can be scaled in half by using a laminate of $[+45,0,-45,90]_S$ . This preserves in-plane and flexural moduli of the material. However, conventional guidelines discourage clumping plies in laminate design. Thus, ply thickness is not readily scaled and even if scaling rules could be developed for laminates based on ply-level scaling, they would be of little or no use. Making the laminate thinner by dividing the existing stacking sequence is termed sublaminate-level scaling. For example a $[+45,0,-45,90]_{2S}$ laminate can be scaled in half using a laminate of orientation $[+45,0,-45,90]_S$ . With this approach, in-plane properties are preserved, but the flexural moduli are distorted. Thus it is important to study the effects of ply-level versus sublaminate-level scaling. It has been shown (reference 1) that even though the in-plane moduli are equal for specimens scaled in both ways, the tensile strength of ply-level scaled laminates decreases as specimen size and thickness increase (although this difference

becomes smaller as more 0° load-carrying plies are added). For angle-ply laminates using sublaminate-level scaling, the opposite was found to hold, that is as the specimen size and thickness increased, so did the strength (reference 2).

Bucinell et. al. (reference 5) showed that using the Mass-Length-Time (MLT) fundamental dimension system, the dimensions scale as $\lambda^3 M_1 = M_2$, $\lambda L_1 = L_2$ and $\lambda T_1 = T_2$ where $\lambda$ is the scaling size ratio. The subscript 1 refers to the smaller model. This model will be utilized in the present study as shown in Table 1 to give the relationships between some key parameters to be examined in this study.

## Experiments

### Material

The laminates used in this study were composed of Hercules™ IM-7 / 8551-7 carbon/epoxy unidirectional prepreg. Hercules 8551-7 is an amine-cured, toughened epoxy resin system which has a service temperature of 93° C (200° F).

The quasi-isotropic composite specimens used in this study consisted of both single and double stack lay-ups. The difference between the single and double stack specimens is the number of plies for each fiber orientation. A single stack specimen has one ply per fiber orientation (i.e. $[45/0/-45/90]_{ns}$), while a two stack specimen has two (i.e. $[45_2/0_2/-45_2/90_2]_{ns}$). The double stack specimens allowed the ply thickness to be geometrically scaled. The actual stacking sequences of the laminates with specimen designations are listed in Table 2.

The laminates were cured in an autoclave using the manufacture's recommended cure cycle and then cut into 6 inch square specimens using a diamond blade wet saw.

The properties of the material used are listed in Table 3.

## Mechanical Testing

All static-indentation experiments were performed at ambient conditions on an Instron series 8500 servo-hydraulic load frame. The specimens were placed on a platen with a 12.7 cm (5 in.) square opening as shown in figure 1. A 12.7 mm (1/2 in.) diameter hemi-spherically tipped indentor (tup) was used. This fixture was designed to produce bending of a simply-supported square plate under a central load. All of the loads were applied in stroke control at a rate of 1.27 mm/min (0.05 in./min.). Transverse displacement measurements for the 8 and 16 ply specimens were taken at intervals of approximately 223 N (50 lbs.). The transverse displacements of the 32 and 64 ply specimens were measured at intervals of approximately 445 N (100 lbs.). Once a significant drop in load (greater than 10%) was observed, the specimens were unloaded at the same load rate in order to determine the system's hysteresis. Repeatability was determined by reloading a new specimen and re-running the test.

To study scaling effects, the 12.7 cm (5 in.) opening platen was replaced by a 6.35 cm (2.5 in.) opening platen, and the indentor (tup) diameter was changed to 6.35 mm (1/4 in.). Since repeatability was studied in the first set of experiments, only one specimen of each thickness was tested using the smaller opening. The transverse displacement measurements were performed in the same fashion as previously described for the larger opening.

A series of impact tests were performed on the 8, 16, and 32 ply specimens to determine whether or not the low velocity impact events where quasi-static in nature. The impact tests were performed using a 22.25 N (5 lb.) drop weight with a 12.7 mm (1/2 in.)

diameter impactor (tup) and the 12.7 cm (5.0 in.) plate opening. The height needed to achieve the desired impact load was calculated using energy levels found in the quasi-static indentation test. The energy was found by integrating the best fit curve of each displacement versus load plot. All heights were checked on dummy specimens to verify impact loads and adjusted if needed. The 8 and 16 ply specimens were checked for repeatability of mechanical response to a given impact event.

### X-Ray Analysis

After static indentation or impact testing, a Zinc Iodide (ZnI) solution was applied to the center of the specimens. This solution, which is opaque to x-rays, seeps into microcracks and delaminations. Film was placed behind the specimen; and, upon exposure to an x-ray source, the damage is highlighted in the negatives. The total planar area of the delamination was determined from the negatives. For specimens that did not have visible surface damage, a small hole was drilled through the center of the specimen to allow the dye penetrant to reach any internal damage that may have been present.

### Microstructure Analysis

For a through-the-thickness assessment of the damage, the specimens were cross-sectioned, polished and examined under a microscope.

## Results

Table 4 summarizes the results from the static indentation tests that were performed in this study. Specimen I.D.s are indicated in the table. Specimens with an "A" designation were one stack supported over a 12.7 cm (5 in.) square opening and those with a "B"

designation were two stack specimens supported over the same opening. Specimens with a "C" designation were one stack supported over the 6.35 cm (2.5 in.) opening and those with a "D" designation were two stack specimens supported over the smaller opening. A cursory examination of Table 4 indicates that for a given thickness and support size, the maximum load and deflection to the first load drop were fairly repeatable for a given stacking sequence. The maximum load is defined as the highest transverse load that each specimen sustained before a sharp drop in load, signifying the onset of damage. Maximum loads and deflections for the 1 and 2 stack specimens differ as much as 26% indicating that ply-level scaling will give different results for a given transverse loading condition. The dent depth results were repeatable in some specimens, but not in others. Delamination area was also fairly repeatable for a given stacking sequence, but a large difference is noted between the 1 and 2 stack specimens.

### Scaled Load-Displacement Data

As expected, the specimens supported over the 6.35 cm (2.5 in.) opening indented with a 6.35 mm (.25 in.) diameter tup had a much higher stiffness for a given thickness compared to the specimens supported over the 12.7 cm (5.0 in.) opening due to the smaller support dimensions. Thus to compare tests for different opening sizes, thickness, etc., the scaling parameters must be applied. From Table 1, displacement scales linearly while the load scales to the second power. Figure 2 is a load-displacement plot comparing the 2 stack 16 ply specimens supported over the 12.7 cm (5 in.) opening with the scaled single stack 8 ply specimens supported over the 6.35 cm (2.5 in.) opening. The displacement data for the smaller opening and thickness has been multiplied by $\lambda = 2$ and the load data has been multiplied by $\lambda^2 = 4$ according to the scaling rules. The maximum load of the 8 ply scaled specimens is found to be 35% larger than the maximum load of the 16 ply specimens and

the corresponding displacement is 11% larger for the 8 ply scaled specimen. Hysteresis is also larger for the 8 ply scaled specimens. The general shape of the curves are similar.

Figure 3 compares the scaled 16 ply specimen data to the 32 ply specimen data and figure 4 compares the scaled 32 ply specimen data to the 64 ply specimen data. The scaled data yields larger values of load and displacement, but less so for displacement values. The displacement values for the scaled 16 ply specimen are 2% greater than for the 32 ply specimen, and the scaled values for the 32 ply specimen are 8% greater than for the 64 ply specimen. The corresponding maximum loads are 19% and 12% larger, respectively. The shapes of the scaled 32 ply and 64 ply curves (figure 4) are different in that the stiffness of the 64 ply specimen decreased more than that of the scaled 32 ply specimen.

### One and Two Stack Comparisons

In figures 5-10, the unscaled results from the 1 and 2 stack specimens are compared for the same thickness and opening size. If the ply thickness does not need to be scaled, then these results should be equivalent. When indentation rather than flexure dominates as in the case of the 6.35 cm (2.5 in.) opening specimens and the 64 ply specimen supported over the 12.7 cm (5.0 in.) opening, ply thickness has little effect. The loading curves are similar for all of the tests, however the amount of hysteresis is much larger for the 16 and 32 ply one stack laminates supported over the 12.7 cm (5.0 in.) opening than for the equivalent two stack laminates indicating that more damage was formed in the one stack laminates. In the other cases, the hysteresis is larger for the two stack laminates indicating that more damage was formed in the two stack laminates.

## Delamination Area Results

The delamination area versus maximum transverse load data for the 12.7 cm (5 in.) opening 2 stack specimens are given in figure 11. These data indicate that good repeatability existed in the specimens examined and that a general trend of increasing damage size with increasing maximum load was observed. The 2 stack specimens appear to sustain more damage at a given transverse load than the 1 stack specimens. The 2 stack 32 ply specimens demonstrated an increase of 50% over the 1 stack 32 ply specimens. The 2 stack 64 ply specimens demonstrated an increase of 65% over the 64 ply 1 stack specimens.

The delamination area versus maximum transverse load data for the 6.35 cm (2.5 in.) opening 1 and 2 stack specimens are given in figure 12. Since only one data point was used for each specimen size, no qualitative measurements of repeatability exists. For these data, a less well-defined trend is found than in the data for the 12.7 cm (5.0 in.) opening specimens. More testing needs to be performed to see if this is due to scatter in the data or to some sort of actual trend where, at some point, the damage area actually decreases with increasing transverse load. The differences between the 1 and 2 stack specimens are also much greater than those supported over the 12.7 cm (5.0 in.) opening. The same trend of less delamination area being present in the 1 stack specimens still exists, but the 32 ply 2 stack specimens show a 250% increase and the 64 ply 2 stack specimens show a 167% increase in delamination area over the 1 stack specimens.

## Dent Depth Results

Dent depth results for the 12.7 cm (5.0 in.) opening 1 and 2 stack specimens are given in figure 13. The repeatability in these data are not as good as the data for

delamination area. Figure 14 shows dent depth data for the specimens supported over the 6.35 cm (2.5 in.) opening. Trends in the data are difficult to find, especially for the 1 stack specimens.

### Scaled Delamination and Dent Depth Data

Figure 15 shows the delamination data from the 1 stack specimens supported over the 6.35 cm (2.5 in.) opening scaled by $\lambda$=2. According to the principle of similitude discussed earlier, these data should be identical to that of the 2 stack specimens supported over the 12.7 cm (5.0 in.) opening. From the figure, it is obvious that as the specimen's thickness increases, the scaled data fall short of what is actually measured in the larger specimens. This could be due to the large variability in the measured results of the 1 stack specimens supported over the 6.35 cm (2.5 in.) opening (see figure 12).

Figure 16 shows the dent depth data from the 1 stack specimens supported over the 6.35 cm (2.5 in.) opening scaled by $\lambda$=2. The actual data from the 2 stack specimens supported over the 12.7 cm (5.0 in.) opening are also plotted. The data are difficult to compare since there exists so much variability, especially in the measured dent depth values of the 1 stack specimens supported over the 6.35 cm (2.5 in.) opening (see figure 14).

### X-Ray and Microstructure Results of Static Loading

By examining the dye penetrant x-ray images coupled with cross-sectional dissection and analysis, a better understanding of the factors that affected the scaling results of damage can be better understood.

The x-rays of the single stack specimens in figures 17-19 indicate that delaminations formed a circular pattern when superimposed upon one another. The overall diameter of the circular regions increased with thickness at the maximum load.

Delamination regions in the two-stack specimens were larger and were more lenticular in shape than similar single stack specimens due to crack growth within the grouped plies. The size of the delaminated regions at maximum load also increased with thickness. For completeness, all x-rays are in the appendix.

Cross-sectional photographs corresponding to the X-rays given in figures 17,18 and 19 are given in figures 20, 21 and 22, respectively. The major differences between the single and double stack specimens for a given thickness is the length and number of delaminations. The single stack specimens had more delaminations (since there are essentially twice as many interfaces), but each delamination is smaller than a delamination in a two stack specimen. Thus qualitatively the total area of delaminated interfaces may be similar, but the planar area of total delamination is different (larger for the two stack specimens).

**Impact Testing Results**

Data from the impacted specimens are given in Table 5. Since all of the impacts were conducted over the 12.7 cm (5.0 in.) opening, a scaling check between select impact specimens cannot be made. These data are presented to compare static indentation results to low velocity impact results. A delamination area comparison of specimens with similar geometry and loads is given in Table 6. From this table it is evident that with the exception of the 8 ply specimens, the impacted specimens sustained much less damage than similar specimens loaded under quasi-static conditions. Also, the transverse forces for impact and quasi-static indentation tests were in good agreement except for the 8 ply specimens. This

raises the question as to the validity of the assumption that low velocity impacts can be simulated by quasi-static indentation tests based on maximum transverse force.

In previous studies it was found that quasi-static and low-velocity impacts produced similar damage (references 11,12). However, at least one recent study has found that for a given transverse load, a quasi-static event will produce more damage than a low velocity impact event (reference 13). The results from this study suggests that more testing needs to be performed to establish the similarity between "quasi-static indentation" and "low-velocity impact" and under what conditions these events produce similar damage in a given specimen.

## Concluding Remarks

This paper examined the scaling of transversely loaded carbon/epoxy plates by utilizing ply-level scaling, or geometrically increasing the thickness of a ply. A scale factor of $\lambda$=2 was examined in scaling from 8 to 16 ply, 16 to 32 ply, and 32 to 64 ply laminates. The laminates were loaded until a sudden drop in the recorded load occurred. The specimens were then unloaded. Force-transverse displacement data was monitored for each test. Post test inspection included measuring dent depth, delamination area as seen by x-rays and cross-sectional examination.

The following conclusions are drawn from this experimental study.

- Static indentation measurements of maximum load, maximum deflection and delamination area were more repeatable than dent depth.
- Scaled values of load and displacement from smaller specimens were greater than those from full-scale specimens. The largest differences were in scaling from 8 ply to 16 ply specimens, which had a 35% larger scaled load and 11% larger scaled displacement.

- Ply-level scaling (grouped plies) is seen to produce more hysteresis in the load-deflection curves of flexurally dominated tests (16 and 32 ply over the 12.7 cm (5.0 in.) opening). For contact dominated loading, little difference between the 1 and 2 stack specimens was seen to exist.
- Not only did dent depths have more variability, they also did not scale well.
- The scaled delamination area was less in all cases than the corresponding full-scale data. The 32 ply scaled data was 71% larger than the 16 ply data.
- The shape of delamination area is more circular in the 1 stack specimens than in the 2 stack specimens. The 2 stack specimens exhibit a more elongated shape due to the creation of longer matrix splitting on the back face of the 2 stack specimens.
- For a given thickness, the 2 stack specimens have half as many interfaces as the 1 stack specimens, thus fewer delaminations were found in the cross-sectional examination. Since an equal amount of energy is dissipated in each case, the 2 stack delaminations tend to be longer.
- Quasi-static indentation to a given transverse load caused a larger delamination area than a low velocity impact of equal transverse load.
- As the specimens went from being supported over the 12.7 cm (5.0 in.) opening down to the smaller 6.35 cm (2.5 in.) opening, more variability existed in the measured values of delamination and dent depth. This suggests that there may be a lower limit of just how small specimens can be in order to be successfully scaled up.

# Appendix

## X-Ray Results

The purpose of this appendix is to show the x-ray results for all of the specimens tested. Figure A-1 shows the x-radiographs of the 1 stack specimens supported over the 12.7 cm (5 in.) opening. Note the circular shape of these delaminations. Figure A-2 shows the x-radiographs of the 2 stack specimens supported over the 12.7 cm (5 in.) opening. Note the elongated shape of these delaminations. Figure A-3 shows the x-radiographs of the 1 stack specimens supported over the 6.35 cm (2.5 in.) opening. Some of these specimens exhibit the elongated shape noted for the 2 stack specimens supported over the larger opening. Figure A-4 shows the x-radiographs of the 2 stack specimens supported over the 6.35 cm (2.5 in.) opening. These show more delamination area is formed in the 2 stack specimens for a given number of plies. Figures A-5 and A-6 show x-radiographs of the impacted specimens and show small delamination area for these specimens.

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Table 1. Scaling Relationship of Key Parameters Examined in this Study

| Parameter | Symbol | Dimensions | Scaling |
|---|---|---|---|
| Transverse Displacement | w | L | $\lambda w_1 = w_2$ |
| Dent Depth | $\delta$ | L | $\lambda \delta_1 = \delta_2$ |
| Delamination Area | A | $L^2$ | $\lambda^2 A_1 = A_2$ |
| Contact Force | P | $ML/T^2$ | $\lambda^2 P_1 = P_2$ |

Table 2. Specimen Lay-Up

| Single Stack Specimens | | | Double Stack Specimens | | |
|---|---|---|---|---|---|
| Specimen | Plies | Panel Lay-Up | Specimen | Plies | Panel Lay-Up |
| 1A | 8 | $[45/0/-45/90]_S$ | 1B | 16 | $[45_2/0_2/-45_2/90_2]_S$ |
| 2A | 8 | $[45/0/-45/90]_S$ | 2B | 16 | $[45_2/0_2/-45_2/90_2]_S$ |
| 3A | 16 | $[45/0/-45/90]_{2S}$ | 3B | 32 | $[45_2/0_2/-45_2/90_2]_{2S}$ |
| 4A | 16 | $[45/0/-45/90]_{2S}$ | 4B | 32 | $[45_2/0_2/-45_2/90_2]_{2S}$ |
| 5A | 32 | $[45/0/-45/90]_{4S}$ | 5B | 64 | $[45_2/0_2/-45_2/90_2]_{4S}$ |
| 6A | 32 | $[45/0/-45/90]_{4S}$ | 6B | 64 | $[45_2/0_2/-45_2/90_2]_{4S}$ |
| 7A | 64 | $[45/0/-45/90]_{8S}$ | | | |
| 8A | 64 | $[45/0/-45/90]_{8S}$ | | | |
| | | | | | |
| 1C | 8 | $[45/0/-45/90]_S$ | 1D | 16 | $[45_2/0_2/-45_2/90_2]_S$ |
| 2C | 16 | $[45/0/-45/90]_{2S}$ | 2D | 32 | $[45_2/0_2/-45_2/90_2]_{2S}$ |
| 3C | 32 | $[45/0/-45/90]_{4S}$ | 3D | 64 | $[45_2/0_2/-45_2/90_2]_{4S}$ |
| 4C | 64 | $[45/0/-45/90]_{8S}$ | | | |
| | | | | | |
| 1E | 8 | $[45/0/-45/90]_S$ | 1F | 16 | $[45_2/0_2/-45_2/90_2]_S$ |
| 2E | 8 | $[45/0/-45/90]_S$ | 2F | 32 | $[45_2/0_2/-45_2/90_2]_{2S}$ |
| 3E | 16 | $[45/0/-45/90]_{2S}$ | 3F | 32 | $[45_2/0_2/-45_2/90_2]_{2S}$ |
| 4E | 16 | $[45/0/-45/90]_{2S}$ | | | |
| 5E | 32 | $[45/0/-45/90]_{4S}$ | | | |
| 6E | 32 | $[45/0/-45/90]_{4S}$ | | | |

Table 3. Properties of the Material Used

| Laminate Property* | SI Units | Customary (FPS) Units |
|---|---|---|
| $E_X$ | 62.7 GPa | $9.1 \times 10^6$ psi |
| $E_Y$ | 62.7 GPa | $9.1 \times 10^6$ psi |
| $\nu_{XY}$ | 0.29 | 0.29 |
| $G_{XY}$ | 24.8 GPa | $3.60 \times 10^6$ psi |

* X$\Rightarrow$ Parallel to 0° fibers

Table 4. Results from Static Indentation Tests

| I.D. | Thickness # plies | Opening Size cm (in.) | Maximum Load N ($lb_f$) | Maximum Deflection mm (in.) | Dent Depth mm (in.) | Delamination Area $cm^2$ ($in.^2$) |
|---|---|---|---|---|---|---|
| 1.27 cm (.5 in.) Tup, "Single Stack" | | | | | | |
| 1A | 8 | 12.7 (5) | 1673 (376) | 7.4 (.290) | .07 (.003) | .24 (.04) |
| 2A | 8 | 12.7 (5) | 1771 (398) | 7.7 (.303) | .05 (.002) | .20 (.03) |
| 3A | 16 | 12.7 (5) | 4052 (1013) | 7.4 (.290) | .43 (.017) | 1.87 (.29) |
| 4A | 16 | 12.7 (5) | 4472 (1005) | 7.2 (.282) | .43 (.017) | 2.26 (.35) |
| 5A | 32 | 12.7 (5) | 12011 (2699) | 6.7 (.262) | 1.1 (.045) | 5.74 (.89) |
| 6A | 32 | 12.7 (5) | 11348 (2550) | 5.7 (.225) | .84 (.033) | 5.55 (.86) |
| 7A | 64 | 12.7 (5) | 29063 (6531) | 4.0 (.156) | .76 (.030) | 7.20 (1.27) |
| 8A | 64 | 12.7 (5) | 29067 (6532) | 4.0 (.158) | .71(.028) | 7.80 (1.12) |
| 1.27 cm (.5 in.) Tup, "Double Stack" | | | | | | |
| 1B | 16 | 12.7 (5) | 4027 (905) | 6.3 (.249) | .18 (.007) | 2.36 (.37) |
| 2B | 16 | 12.7 (5) | 4210 (946) | 6.6 (.258) | .48 (.019) | 3.76 (.58) |
| 3B | 32 | 12.7 (5) | 10969 (2465) | 5.2 (.203) | .61 (.024) | 8.00 (1.24) |
| 4B | 32 | 12.7 (5) | 10720 (2409) | 5.0 (.198) | .53 (.021) | 8.52 (1.32) |
| 5B | 64 | 12.7 (5) | 31737 (7132) | 5.1 (.200) | .84 (.033) | 12.48 (1.93) |
| 6B | 64 | 12.7 (5) | 31746 (7134) | 5.0 (.197) | .74 (.029) | 11.55 (1.79) |
| .63 cm (.25 in.) Tup, "Single Stack" | | | | | | |
| 1C | 8 | 6.3 (2.5) | 1344 (302) | 3.6 (.140) | .15 (.006) | 1.00 (.16) |
| 2C | 16 | 6.3 (2.5) | 3280 (737) | 2.8 (.112) | .10 (.004) | 1.20 (.19) |
| 3C | 32 | 6.3 (2.5) | 10391 (2335) | 2.8 (.109) | .20 (.008) | 2.92 (.45) |
| 4C | 64 | 6.3 (2.5) | 18690 (4200) | 2.0 (.080) | .64 (.025) | 2.64 (.41) |
| .63 cm (.25 in.) Tup, "Double Stack" | | | | | | |
| 1D | 16 | 6.3 (2.5) | 3360 (755) | 2.7 (.106) | .30 (.012) | 1.04 (.16) |
| 2D | 32 | 6.3 (2.5) | 10386 (2334) | 3.3 (.129) | .48 (.019) | 9.16 (1.42) |
| 3D | 64 | 6.3 (2.5) | 16523 (3713) | 2.1 (.084) | .46 (.018) | 6.20 (.96) |

Table 5. Data from Impacted Specimens

| Specimen I.D. | Plies | Impact Energy J (ft-lb$_f$) | Maximum Load N (lbs) | Delamination Area cm$^2$ (in$^2$) |
|---|---|---|---|---|
| 1E | 8 | 6.51 (4.8) | 2639 (593) | .76 (.12) |
| 2E | 8 | 6.51 (4.8) | 2336 (525) | .68 (.11) |
| 3E | 16 | 7.86 (5.8) | 4548 (1022) | .68 (.11) |
| 4E | 16 | 7.86 (5.8) | 4543 (1021) | .64 (.10) |
| 5E | 32 | 17.0 (12.5) | 10831 (2434) | 1.00 (.16) |
| 6E | 32 | 17.0 (12.5) | 10880 (2445) | 1.00 (.16) |
| 1F | 16 (2 Stack) | 7.86 (5.8) | No Data | 1.12 (.17) |
| 2F | 32 (2 Stack) | 17.0 (12.5) | 10604 (2383) | 1.60 (.25) |
| 3F | 32 (2 Stack) | 17.0 (12.5) | 9652 (2169) | 1.72 (.27) |

Table 6. Comparison of Static Indentation and Impact Results

| Specimen I.D. | Plies | Load Type | Maximum Load N (lbs) | Delamination Area cm$^2$ (in$^2$) |
|---|---|---|---|---|
| 1E | 8 | Impact | 2639 (593) | .76 (.12) |
| 2E | 8 | Impact | 2336 (525) | .68 (.12) |
| 1A | 8 | Static | 1673 (376) | .24 (.04) |
| 2A | 8 | Static | 1771 (398) | .20 (.03) |
| 3E | 16 | Impact | 4548 (1022) | .68 (.11) |
| 4E | 16 | Impact | 4543 (1021) | .64 (.10) |
| 3A | 16 | Static | 4508 (1013) | 1.87 (.29) |
| 4A | 16 | Static | 4472 (1005) | 2.26 (.35) |
| 5E | 32 | Impact | 10831 (2434) | 1.00 (.16) |
| 6E | 32 | Impact | 10880 (2445) | 1.00 (.16) |
| 5A | 32 | Static | 12011 (2699) | 5.74 (.89) |
| 6A | 32 | Static | 11348 (2550) | 5.70 (.84) |
| 2F | 32 (2 Stack) | Impact | 10604 (2383) | 1.60 (.25) |
| 3F | 32 (2 Stack) | Impact | 9652 (2169) | 1.72 (.27) |
| 3B | 32 (2 Stack) | Static | 10969 (2465) | 8.00 (1.24) |
| 4B | 32 (2 Stack) | Static | 10720 (2409) | 8.52 (1.32) |

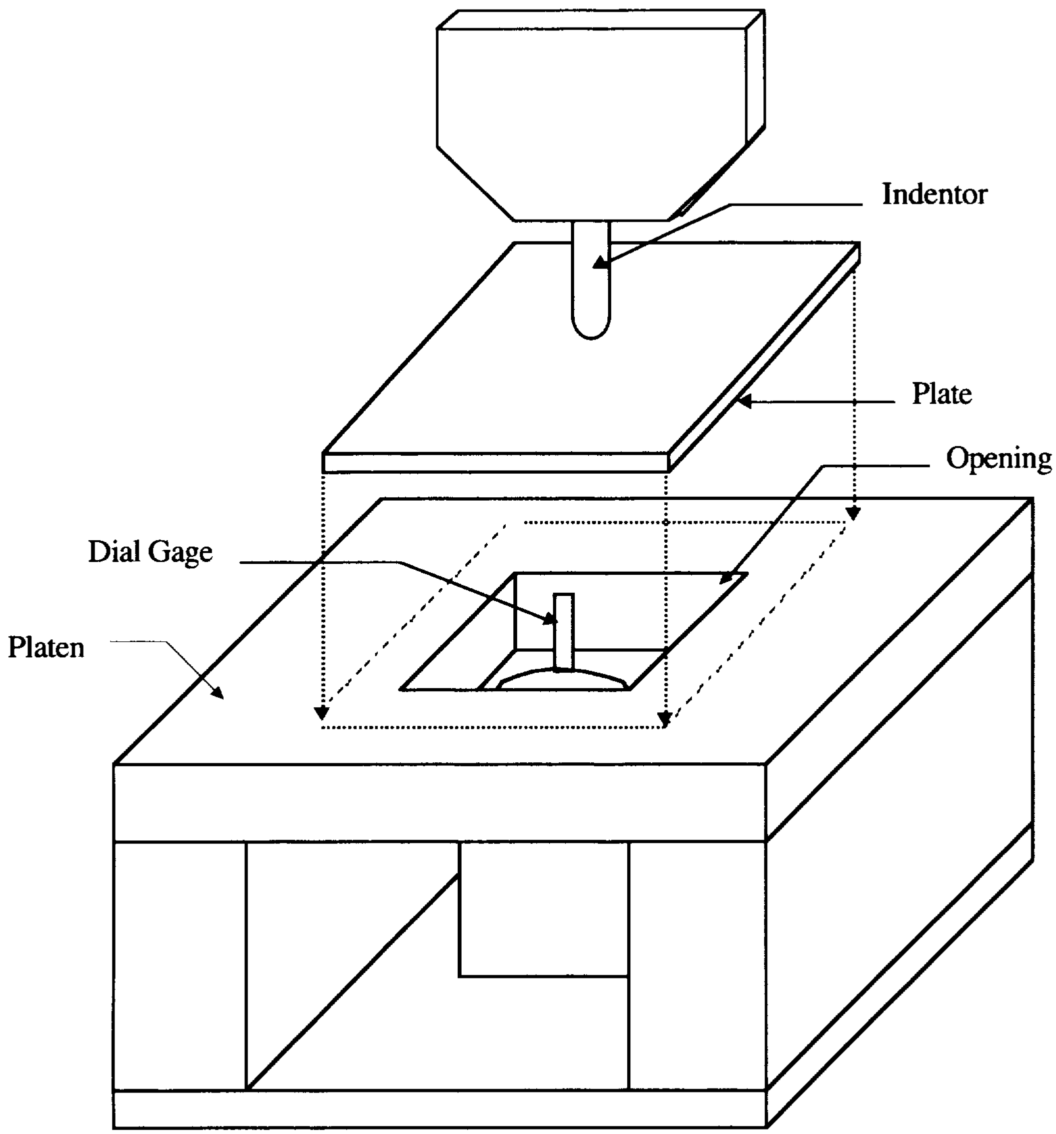



Figure 1. Schematic of test fixture used to perform static indentation tests.

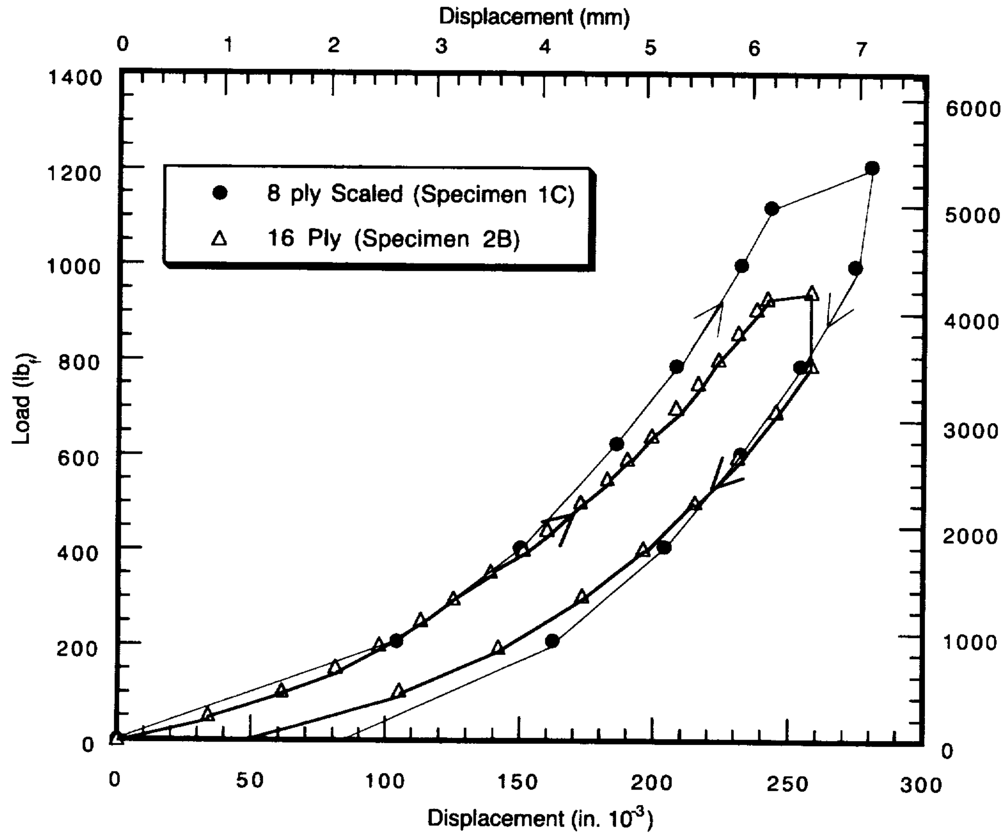



Figure 2. Comparison of scaled 8 ply to 16 ply data.

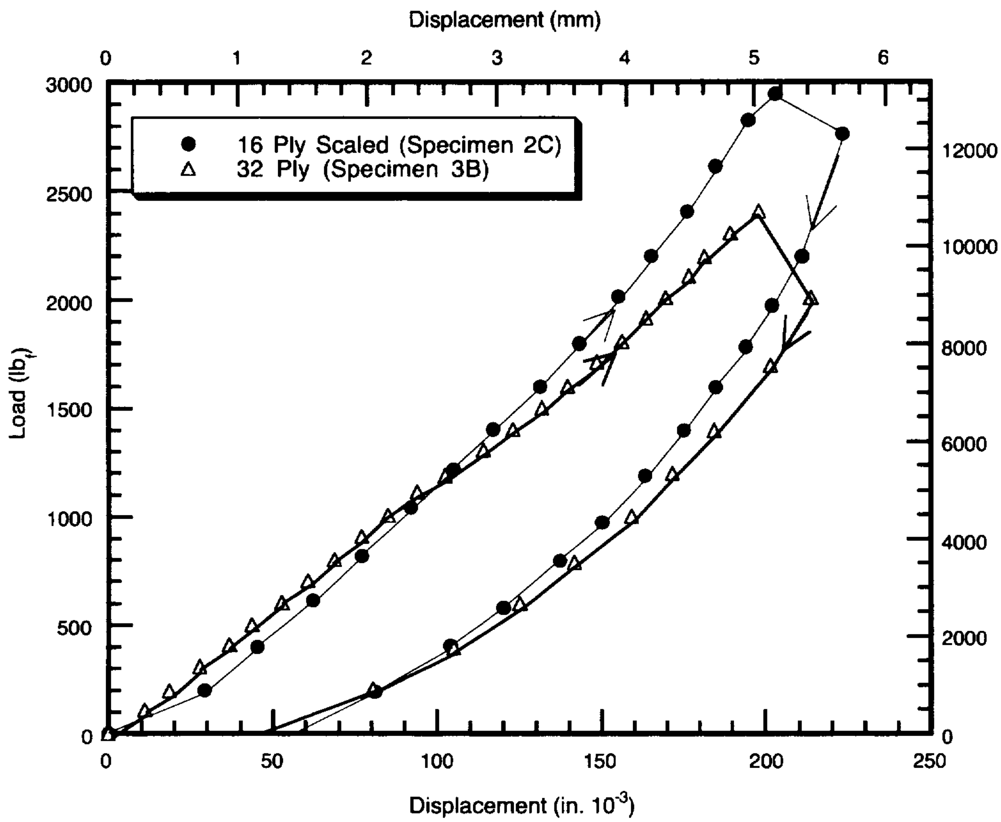



Figure 3. Comparison of scaled 16 ply to 32 ply data.

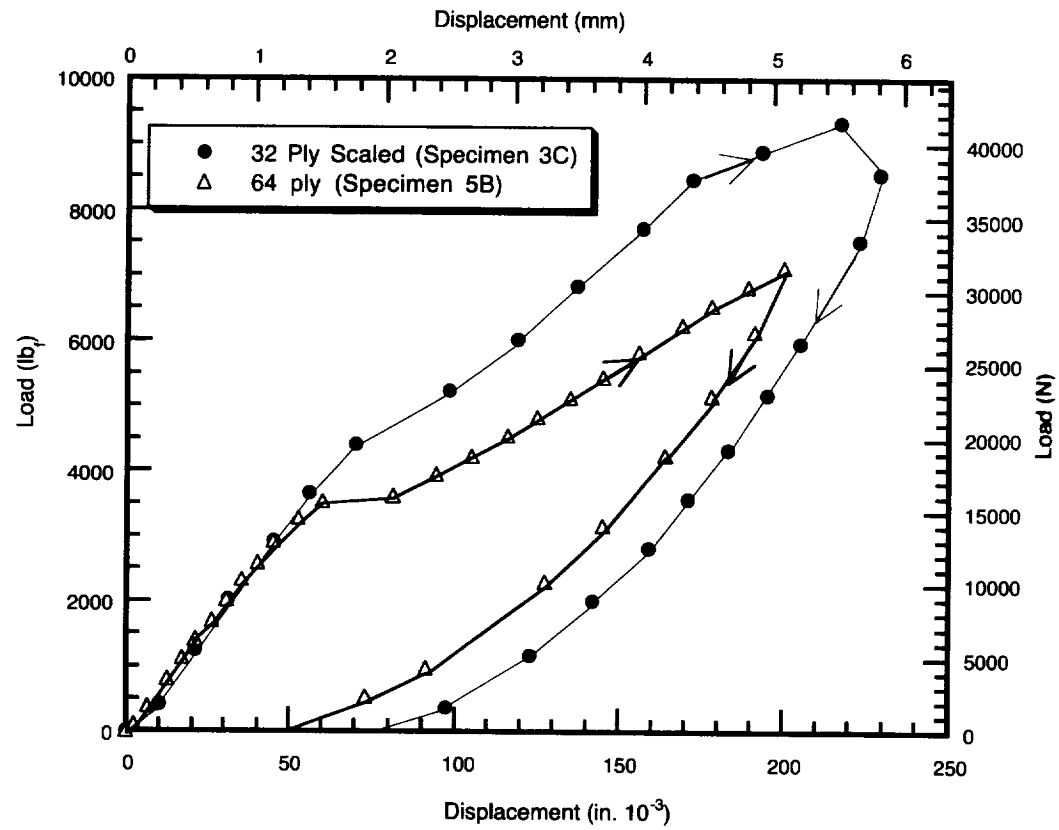



Figure 4. Comparison of scaled 32 ply to 64 ply data.

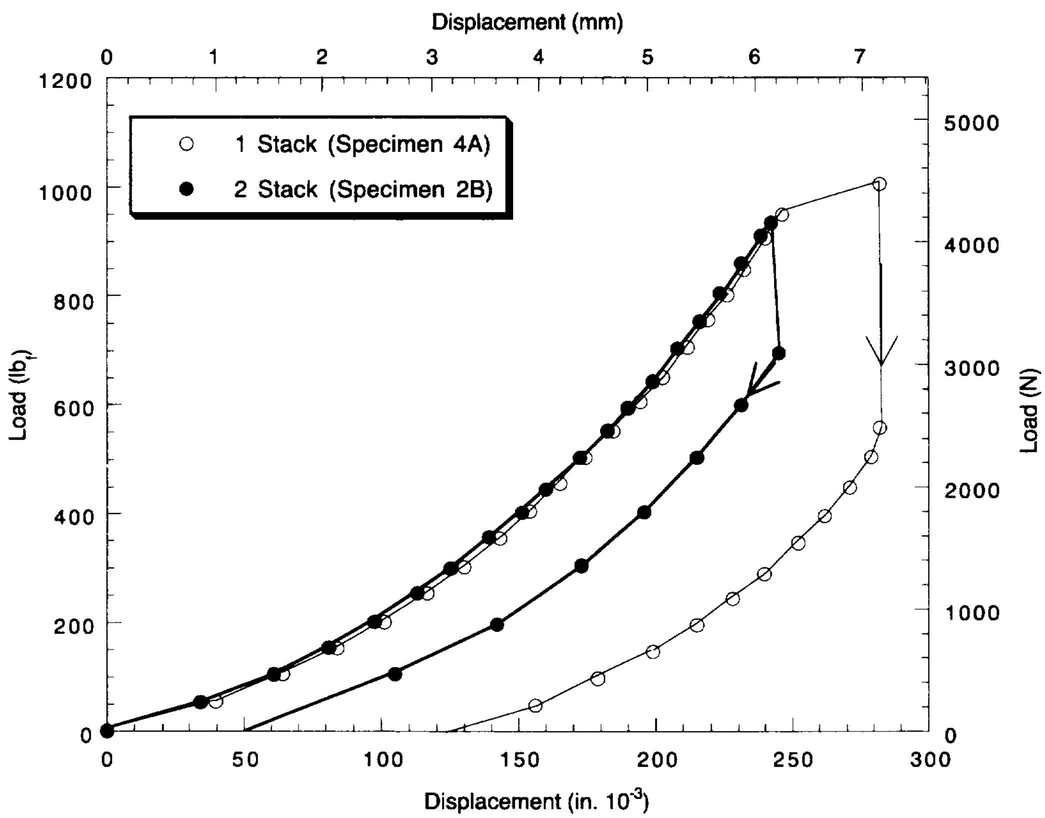



Figure 5. Load/Displacement data for 16 ply 1 and 2 stack specimens supported over the 12.7 cm (5.0 in.) opening.

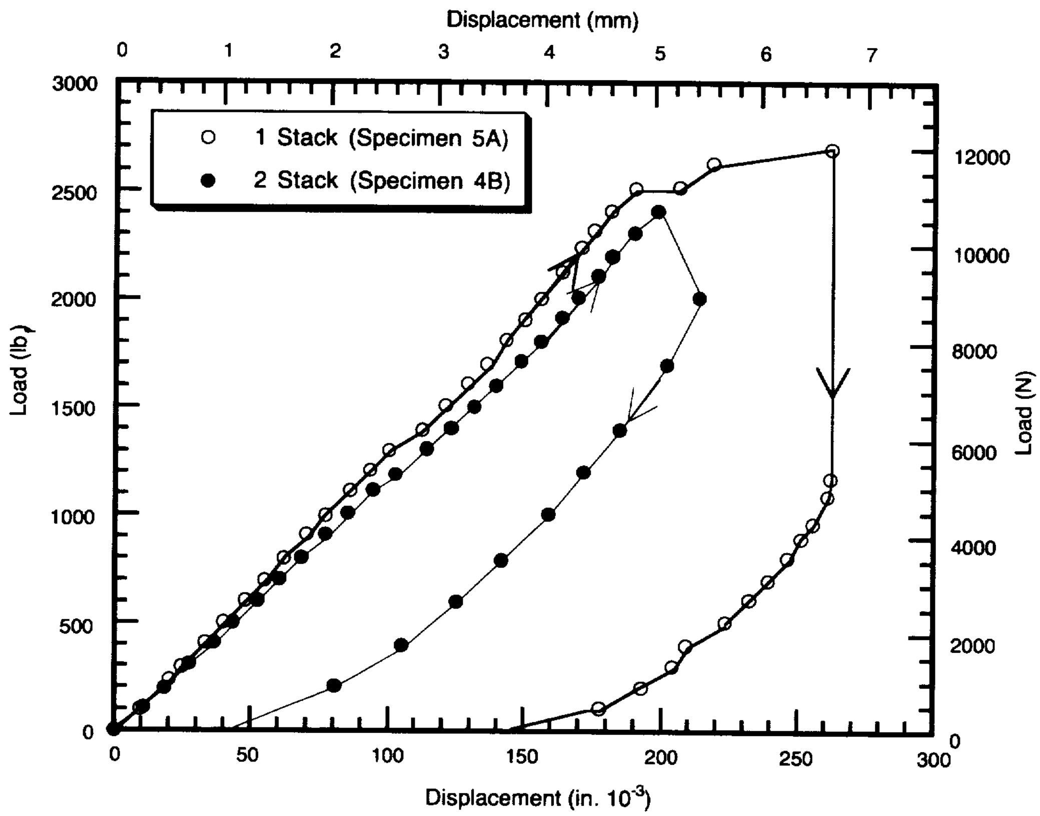



Figure 6. Load/Displacement data for 32 ply 1 and 2 stack specimens supported over the 12.7 cm (5.0 in.) opening.

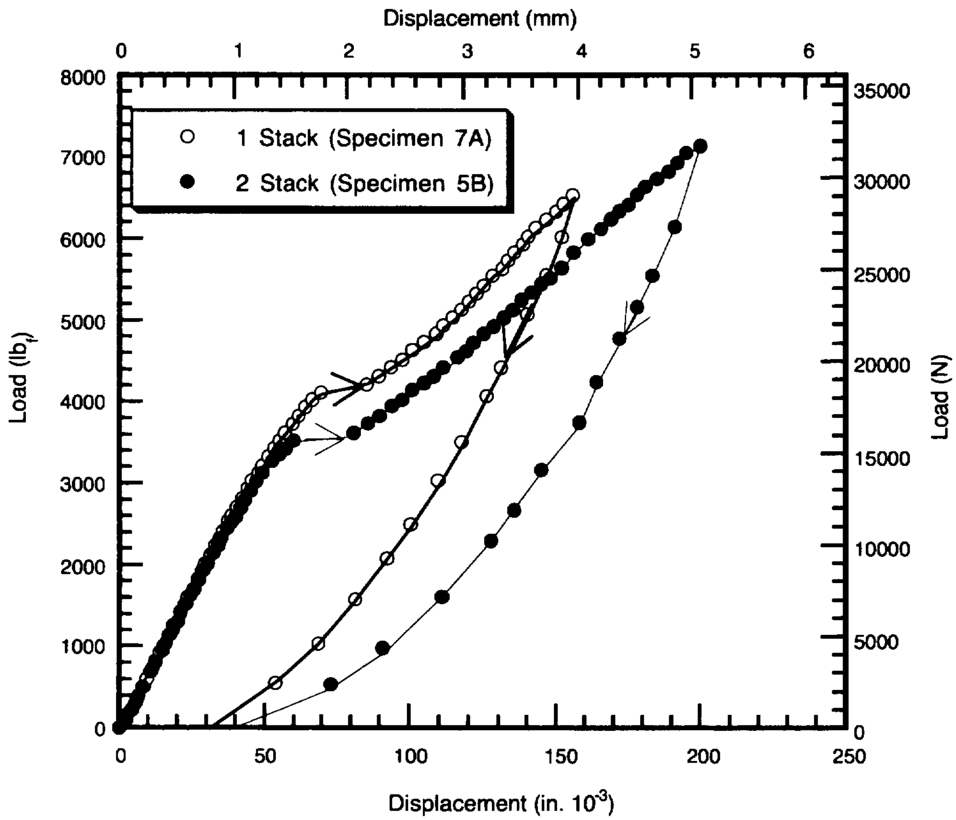



Figure 7. Load/Displacement data for 64 ply 1 and 2 stack specimens supported over the 12.7 cm (5.0 in.) opening.

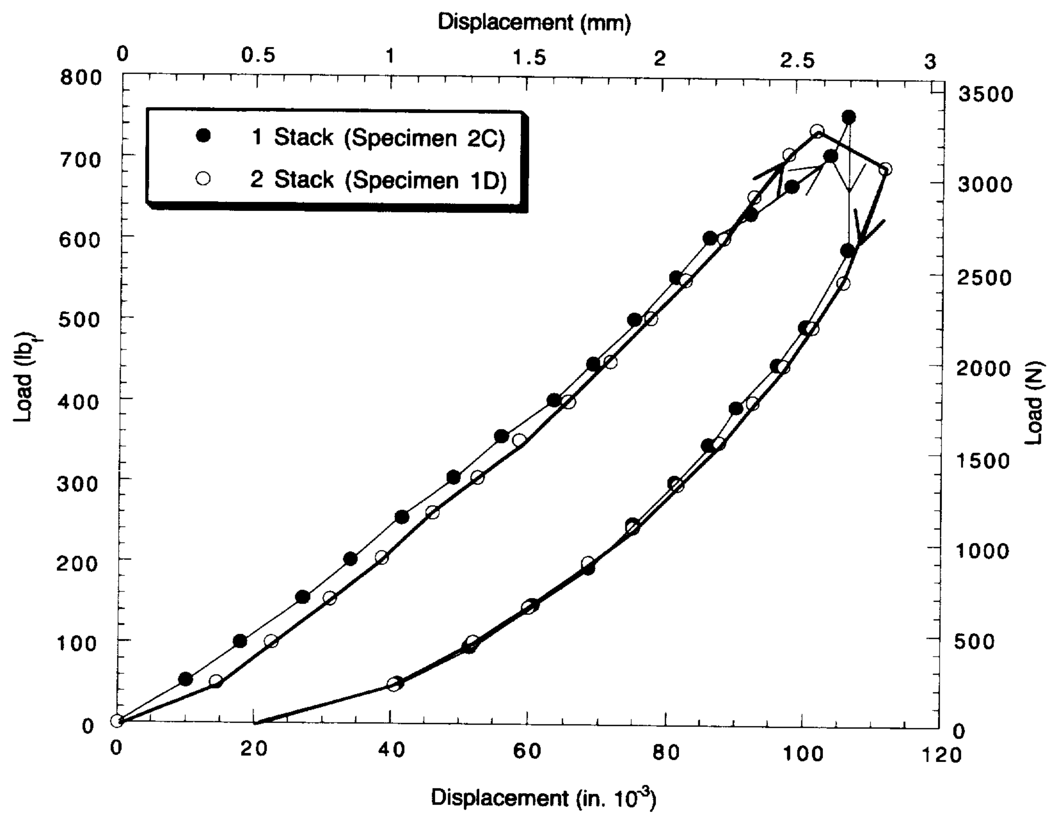



Figure 8. Load/Displacement data for 16 ply 1 and 2 stack specimens supported over the 6.35 cm (2.5 in.) opening.

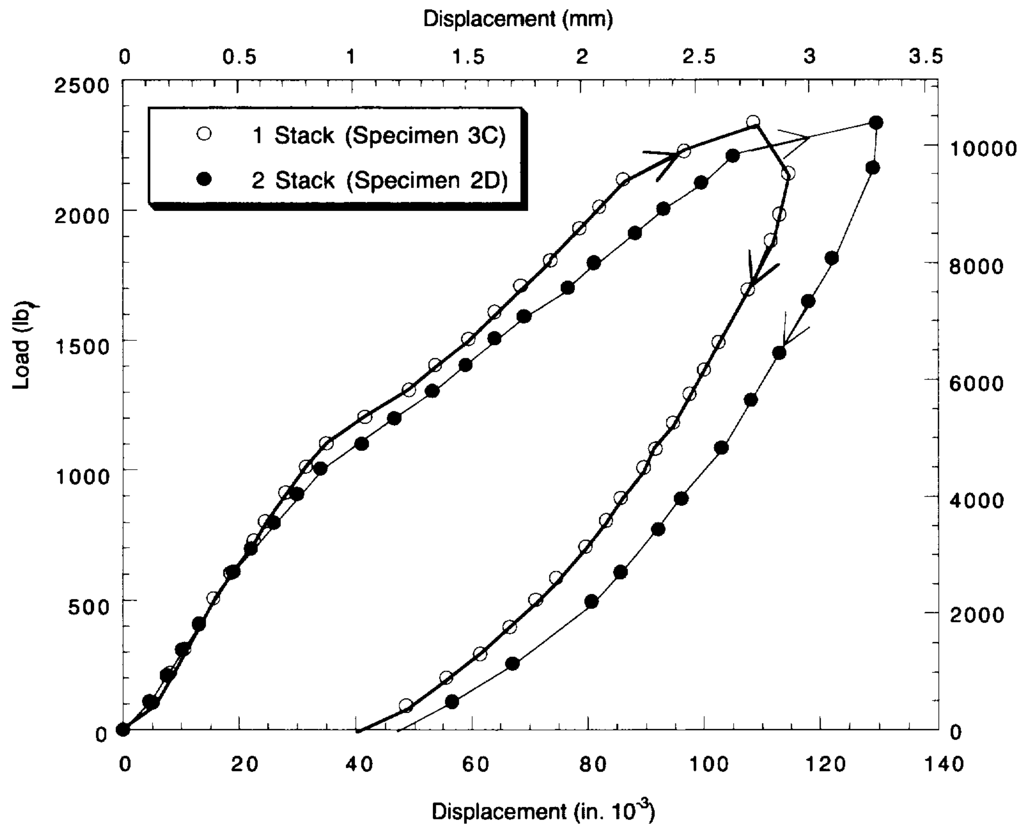



Figure 9. Load/Displacement data for 32 ply 1 and 2 stack specimens supported over the 6.35 cm (2.5 in.) opening.

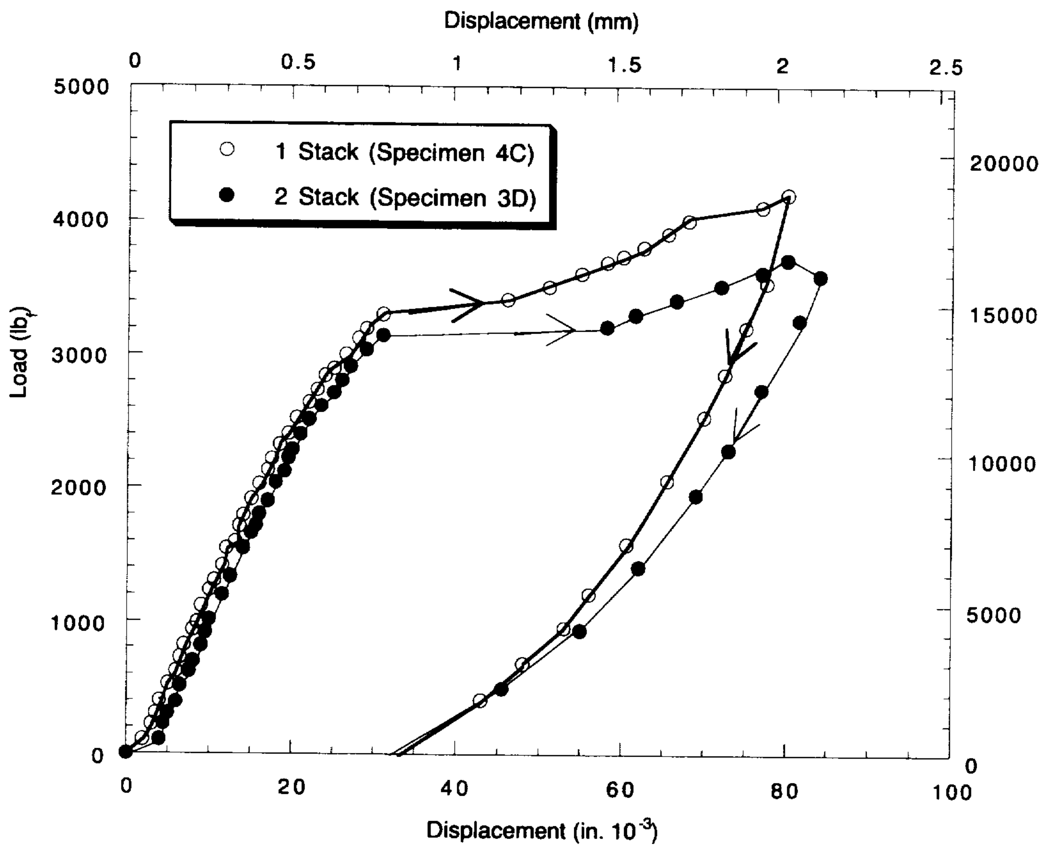



Figure 10. Load/Displacement data for 64 ply 1 and 2 stack specimens supported over the 6.35 cm (2.5 in.) opening.

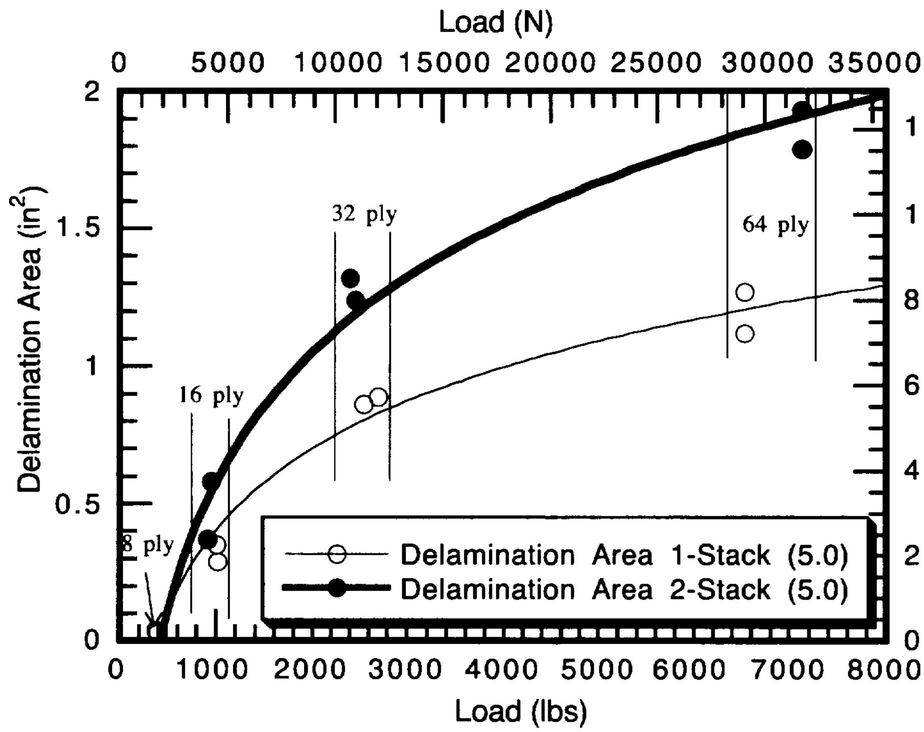



Figure 11. Delamination area versus maximum load for 12.7 cm (5.0 in.) opening (1 and 2 stack panels).

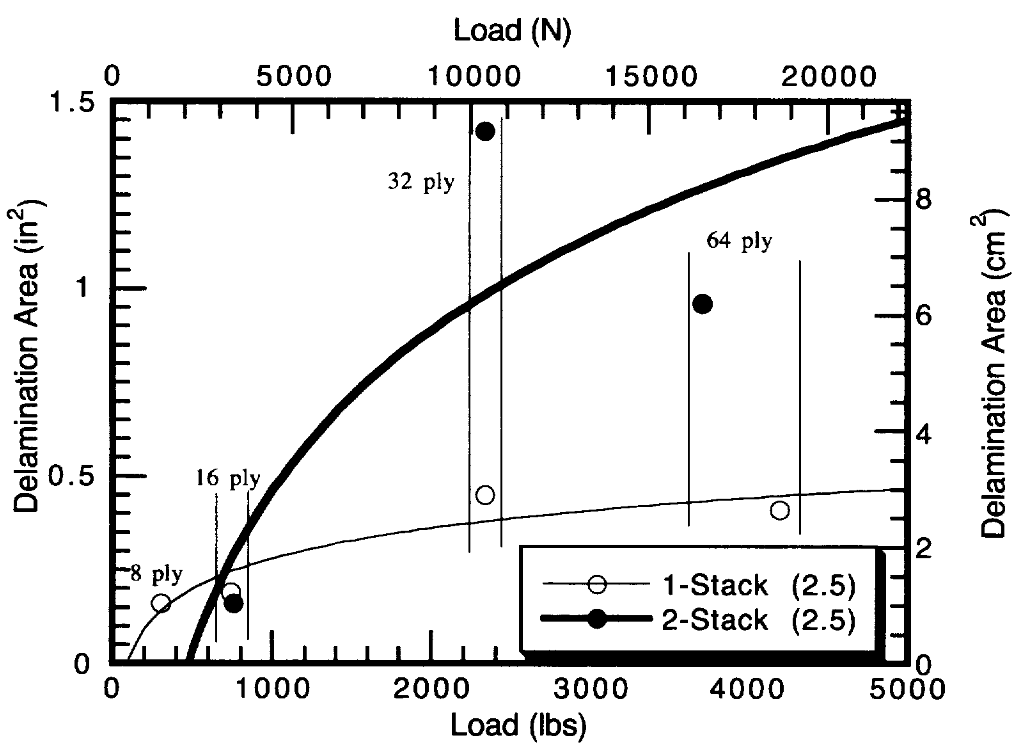



Figure 12. Delamination area versus maximum load for 6.35 cm (2.5 in.) opening (1 and 2 stack panels).

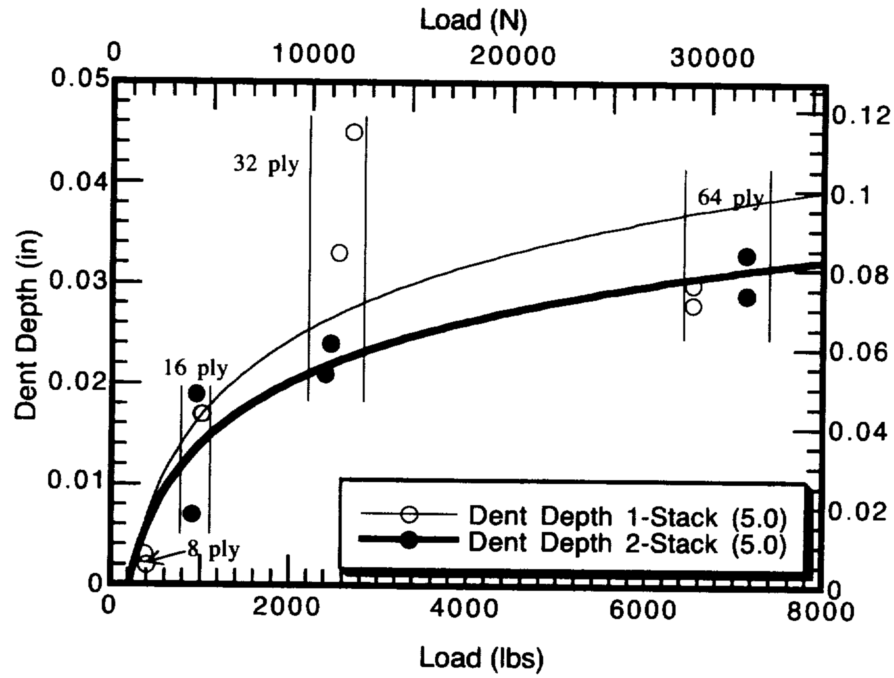



Figure 13. Dent depth versus maximum load for 12.7 cm (5.0 in.) opening (1 and 2 stack panels).

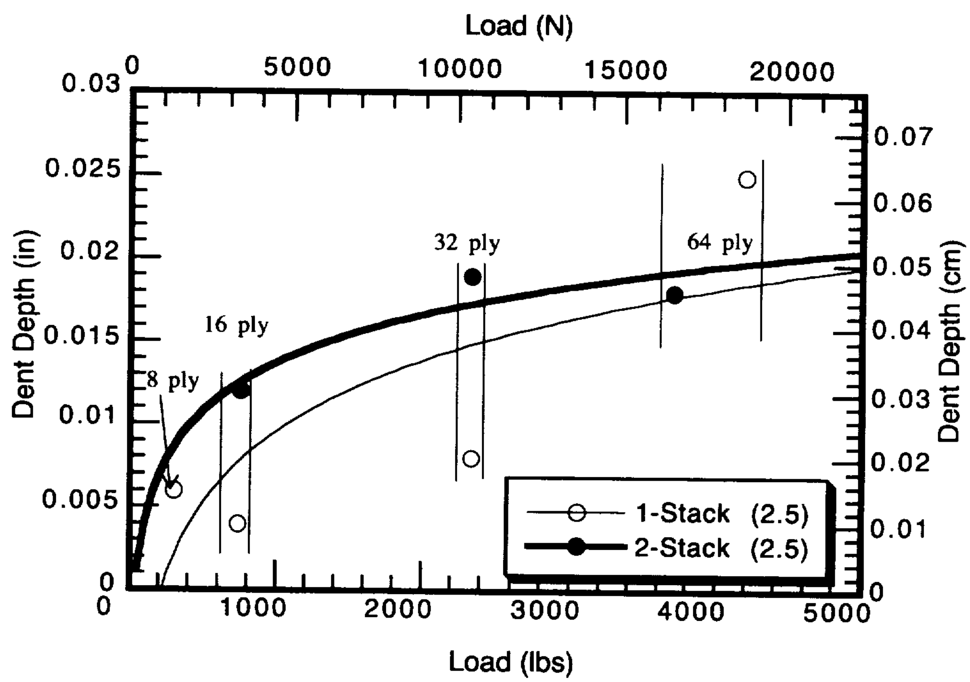



Figure 14. Dent depth versus maximum load for 6.35 cm (2.5 in.) opening (1 and 2 stack panels).

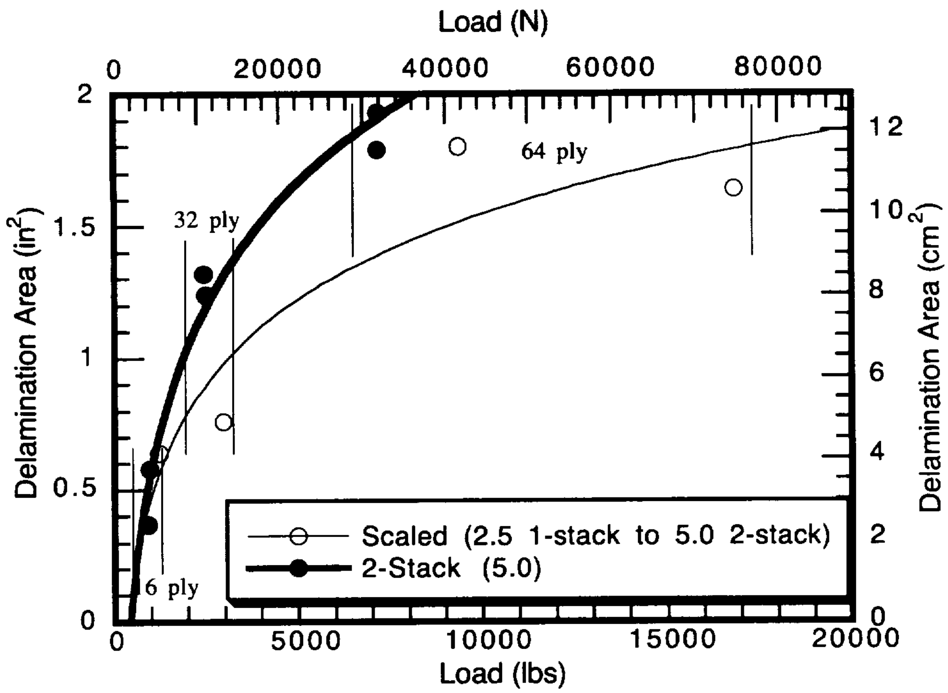



Figure 15. Delamination data from 6.35 cm (2.5 in.) opening 1 stack specimens scaled by $\lambda$=2 and compared to actual delamination data from 12.7 cm (5.0 in.) opening 2 stack specimens.

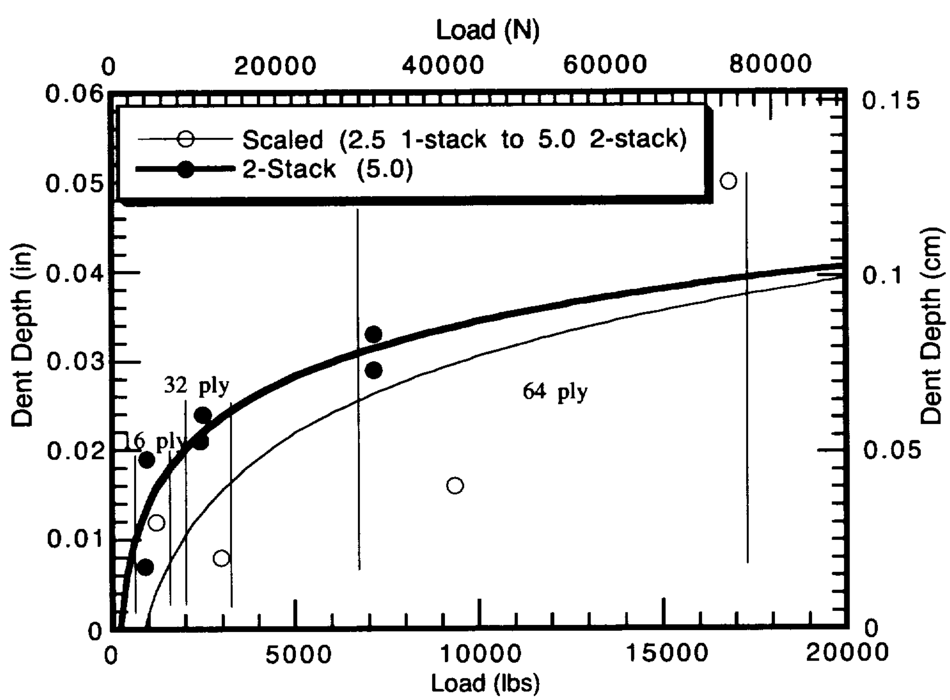
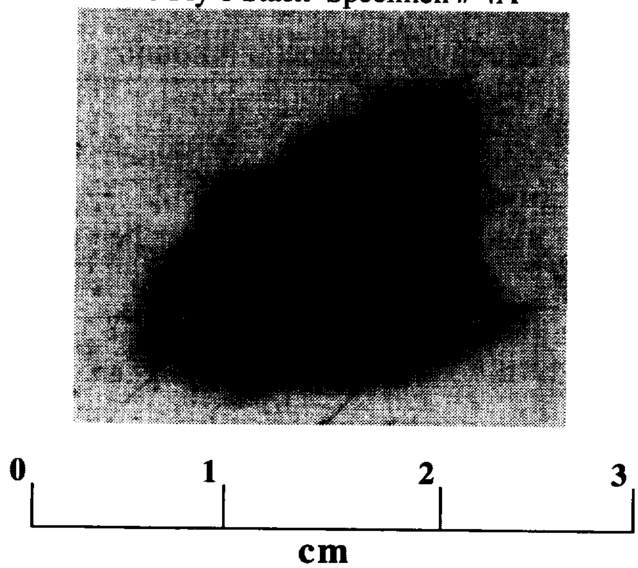



Figure 16. Dent depth data from 6.35 cm (2.5 in.) opening 1 stack specimens scaled by $\lambda$=2 and compared to actual dent depth data from 12.7 cm (5.0 in.) opening 2 stack specimens.

16 Ply 1 Stack Specimen # 4A




16 Ply 2 Stack Specimen # 1B

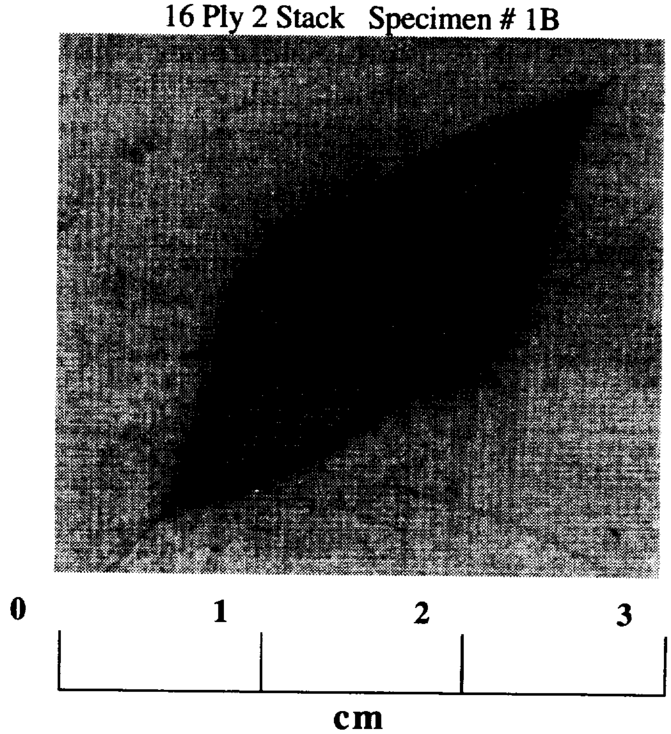
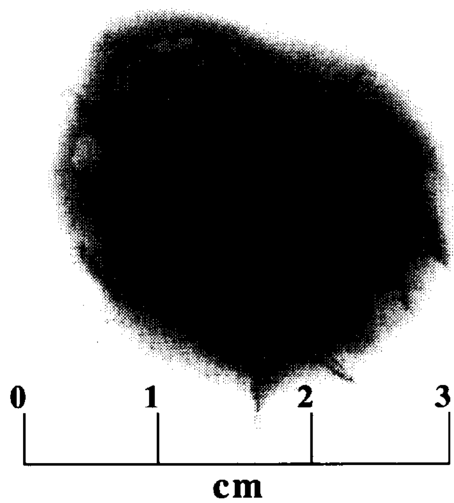



Figure 17. X-ray comparison of 16 ply one and two stack specimens.

32 Ply 1 Stack   Specimen # 5A




32 Ply 2 Stack   Specimen # 3B

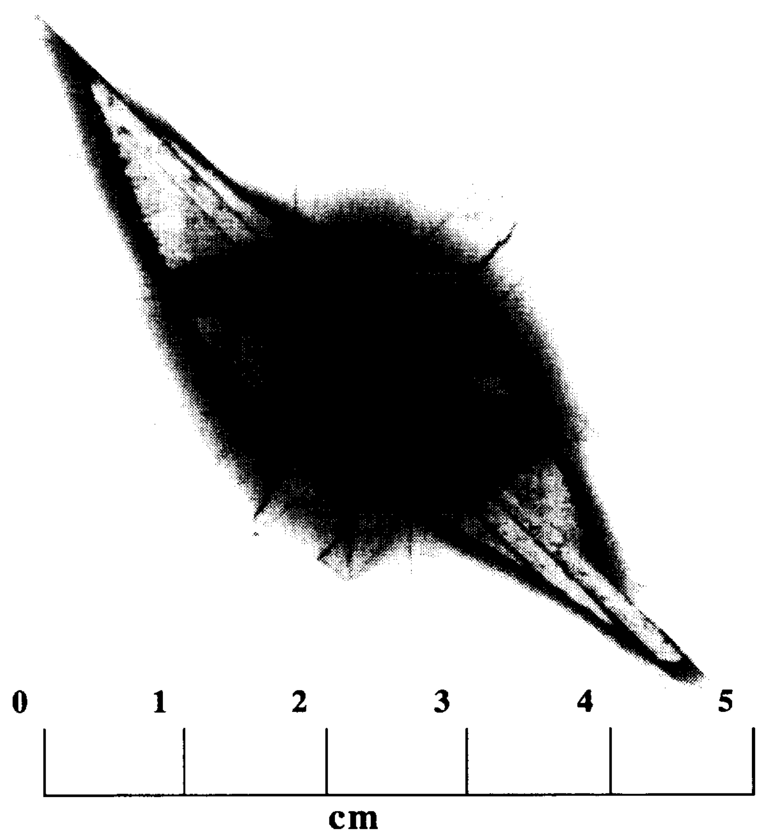



Figure 18. X-ray comparisons of 32 ply one and two stack specimens.

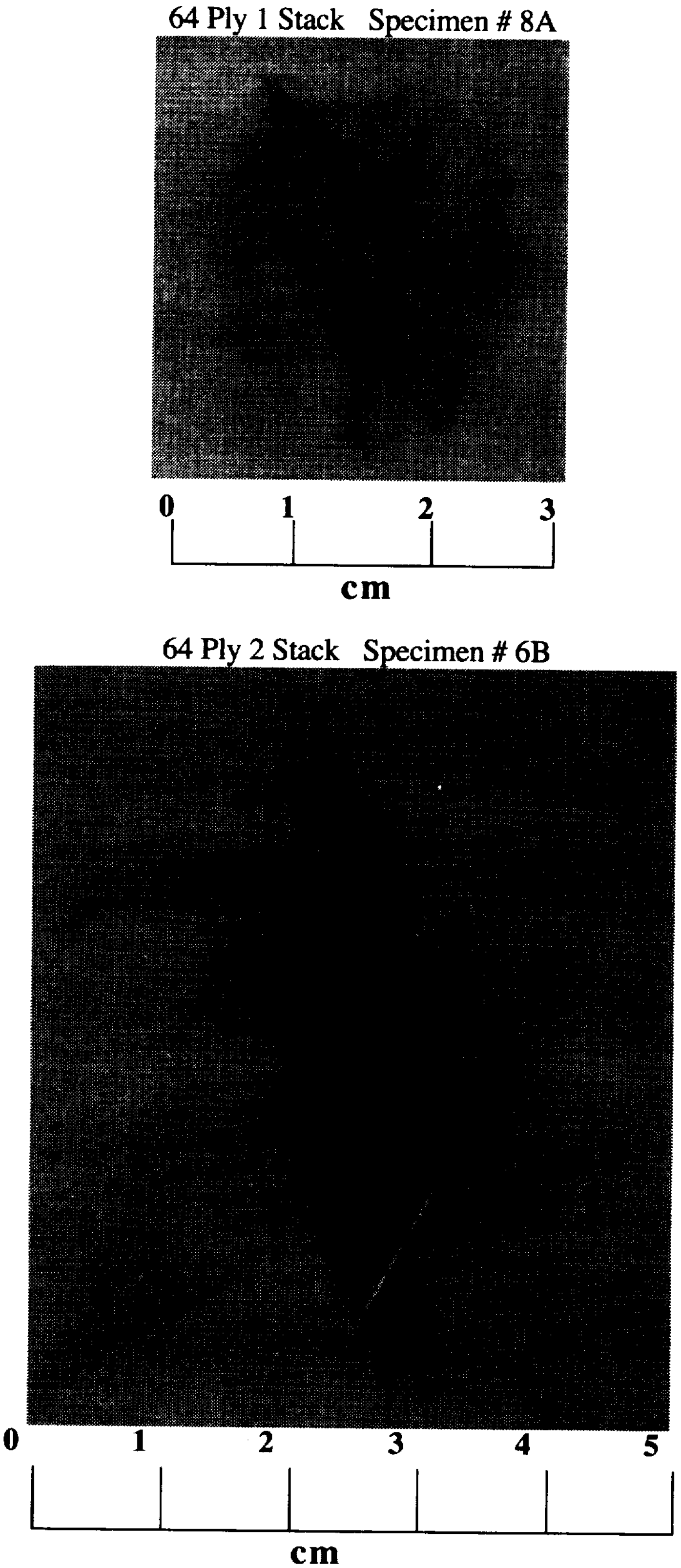
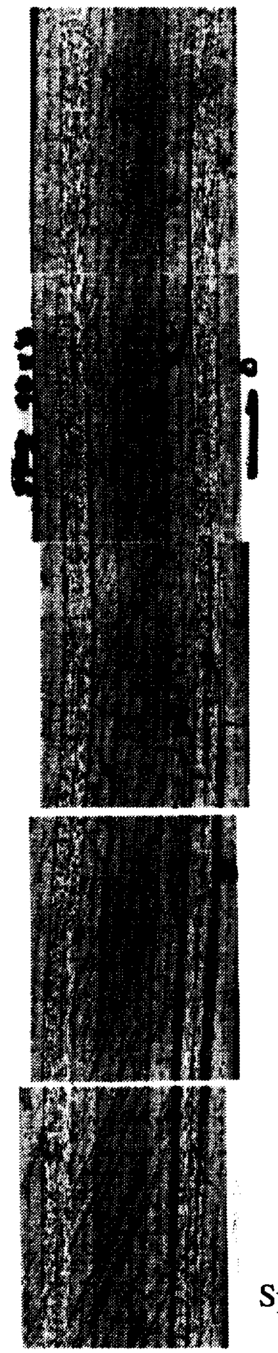



Figure 19. X-ray comparison of 64 ply one and two stack specimens.

Specimen # 4A

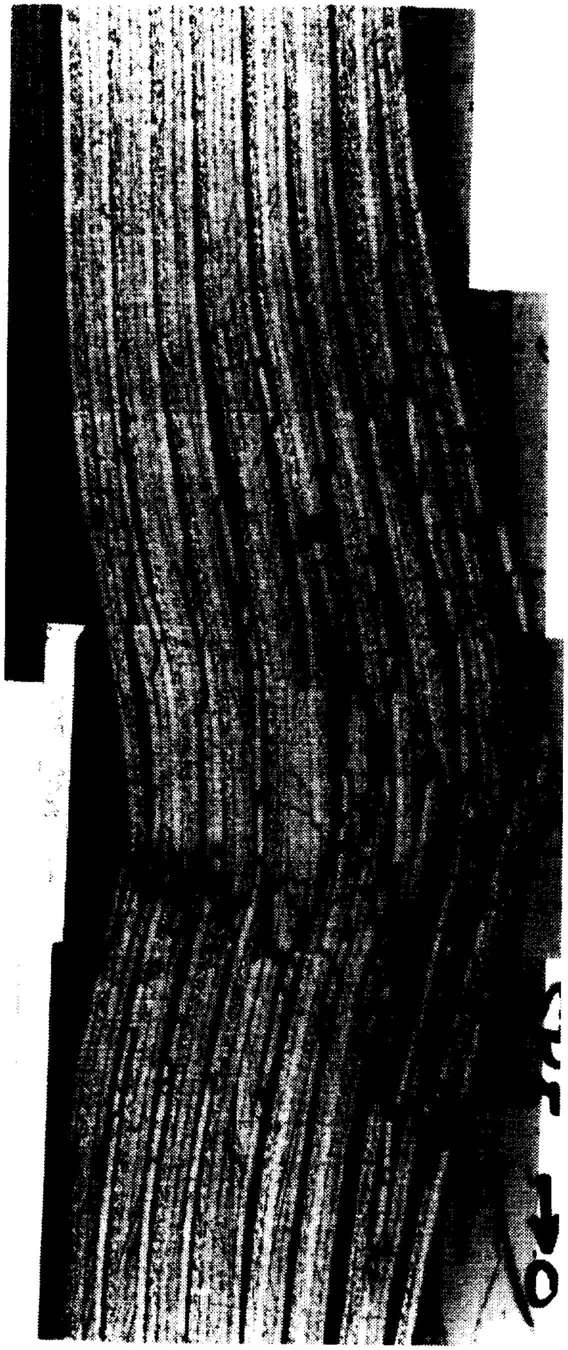
16 Ply 1 Stack



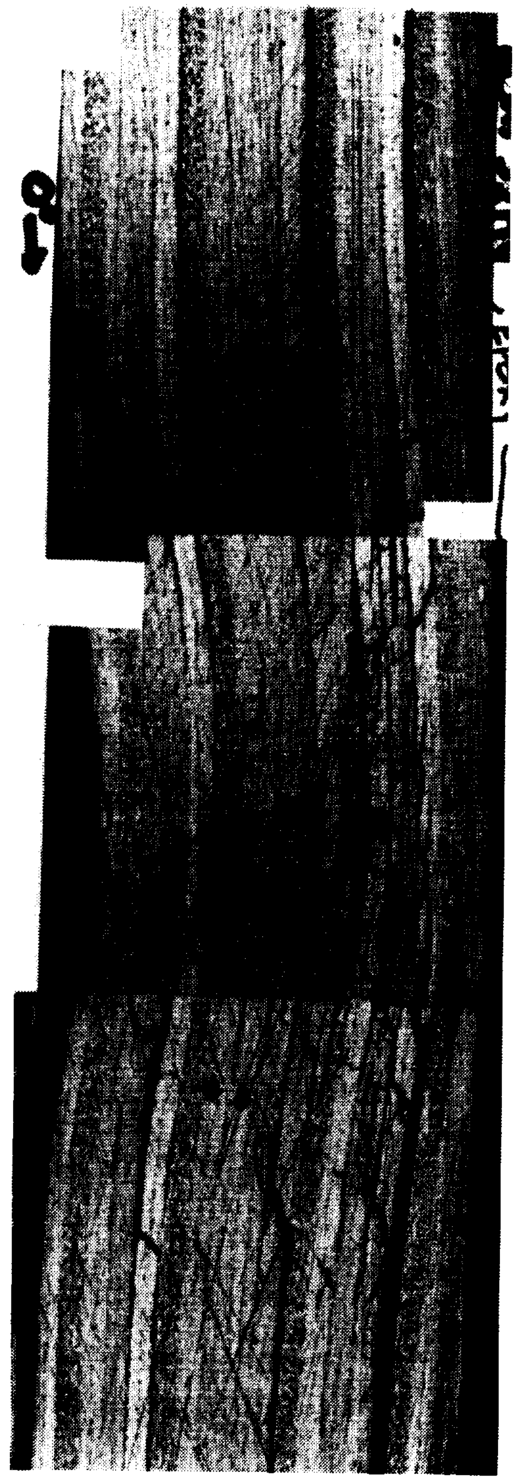
Specimen # 1B

16 Ply 2 Stack

Figure 20. Cross-Sectional views of one and two stack 16 ply specimens.

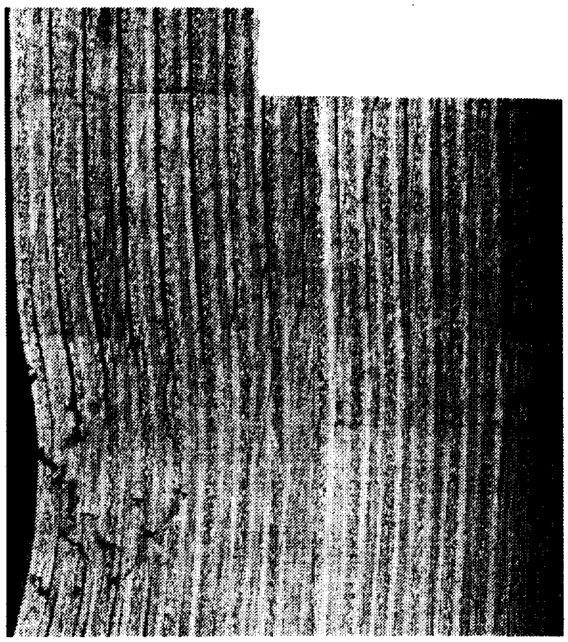


32 Ply 1 Stack Specimen # 5A

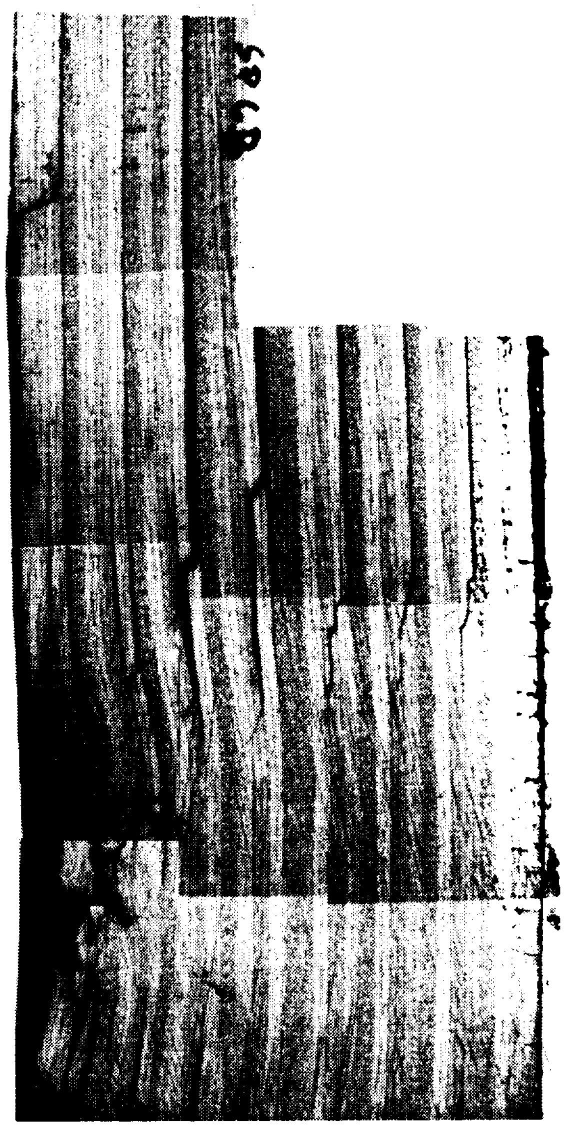


32 Ply 2 Stack Specimen # 3B

Figure 21. Cross-Sectional views of one and two stack 32 ply laminates.



64 Ply 1 Stack Specimen # 8A



64 Ply 2 Stack Specimen # 6B

Figure 22. Cross-Sectional views of one and two stack 64 ply specimens.

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**13. ABSTRACT** (Maximum 200 words)
Scaling effects were considered for 8, 16, 32, and 64 ply IM-7/8551-7 carbon/epoxy composites plates transversely loaded to the first significant load drop by means of both a quasi-static and an equivalent impact force. The resulting damage was examined by x-ray and photomicroscopy analysis. Load-deflection curves were generated for the quasi-static tests and the resulting indentation depth was measured. Results showed that the load-deflection data scaled well for most of the various thicknesses of plates. However, damage did not scale as well. No correlation could be found between dent depth and any of the other parameters measured in this study. The impact test results showed that significantly less damage was formed compared to the quasi-static results for a given maximum transverse load. The criticality of ply-level scaling (grouping plies) was also examined.

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